Incoherent Background Supression in ϕ Production in e+A Collisions

Exclusive, Diffraction, Tagging PWG

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ePIC/EIC Physics Readiness WS

University of Calabria, Physics Department & INFN Cosenza

Introduction

Crucial aspect of program → ability to study gluons

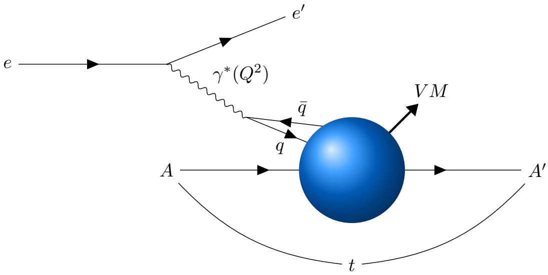
Critical measurement: exclusive vector meson (VM) production in scattering

Exclusive VM Production

$$e + A \rightarrow e' + A' + VM$$

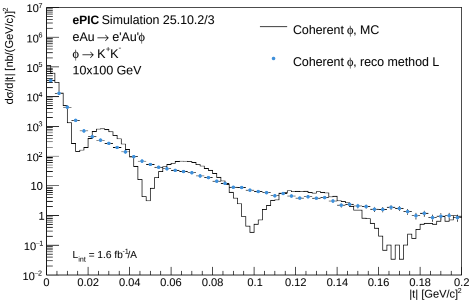
- Complete final state known
- Experimentally clean process

- **Distribution of momentum transfer ($|t|$):**
  - Fourier conjugate to impact parameter
  - Reflects spatial profile
- Gluon imaging → study **onset of saturation**



Motivation

Measurements of the $|t|$ distribution encounter **2 primary challenges**:



1. **Limited resolution in measuring $|t|$**
   - Mainly momentum resolution of e'
     - Scattered very far backward → emerges at small angle
     - Tiny angular error → large p_T error

Yellow Report: best method of $|t|$ reco → method L (blue circles)

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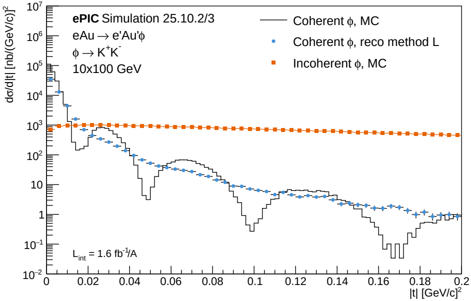

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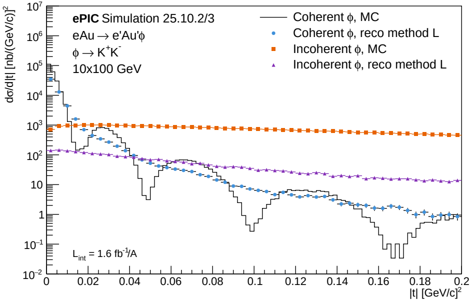

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   - Mainly momentum resolution of e'
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2. **Overwhelming incoherent background**
   - Detector cannot suppress all incoherent production

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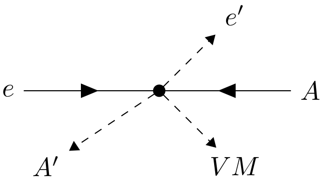
Extracting $|t|$



To access $|t|$: need complete final state

$$|t| = (P_A - P_{A'})^2$$

- **Cannot measure $P_{A'}$**
  - For heavy nuclei $\rightarrow$ stays within beam envelope

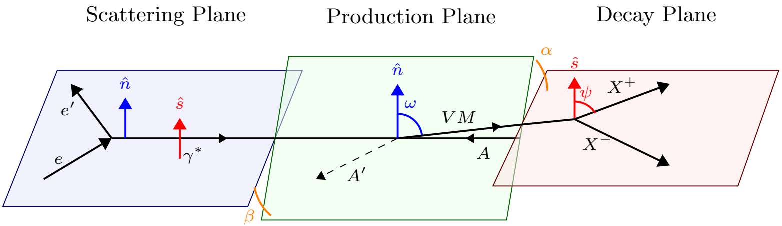
Use Conservation of 4-Momenta

$$P_e + P_A = P_{e'} + P_{A'} + P_{VM}$$

Different Methods:

- $|\boldsymbol{t}|_{BABE}$: $|t| = (P_A - P_{A'})^2$
  - Small error/inaccuracy has large effect on $|t|$
- $|\boldsymbol{t}|_{eX}$: $|t| = [\mathbf{p}_T(e') + \mathbf{p}_T(VM)]^2$
  - Underestimates true t, valid only for small $|t|$ and small Q^2
- **Method L**: $|t|_{\mathrm{corr}} = (P_A - P_{A'}^{\mathrm{corr}})^2$
  - Only applies to coherent events

New Method



Note: $\theta_{max} \rightarrow \omega_{max}$

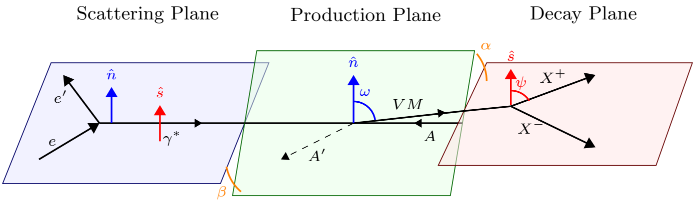
- Measure $|t|$ component along normal direction ($\hat{n}$) of electron scattering plane
- $|t|_{\hat{n}}$ unaffected by momentum resolution
  - Eliminate momentum resolution contribution from e'

Define $\hat{n}$:

$$\hat{n} = \hat{p}_e \times \hat{p}_{e'}$$

arXiv:2502.15596

Projection Technique



Method L:

$$|t|_{\mathrm{corr}} = (P_A - P_{A'}^{\mathrm{corr}})^2$$

$|t|_{BABE}$:

$$|t| = (P_{VM} + P_{e'} - P_e)^2$$

Define $\hat{n}$:

$$\hat{n} = \hat{p}_e \times \hat{p}_{e'}$$

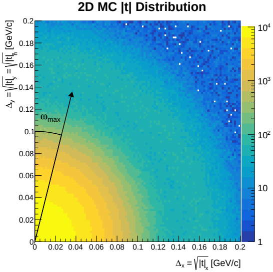
$$|t|_{\hat{n}} = [(P_{VM} + P_{e'} - P_e) \cdot \hat{n}]^2$$

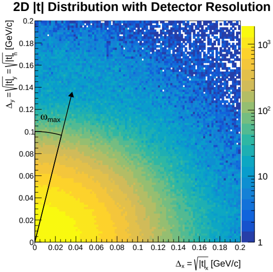
$$|t|_{\hat{n}} = (P_{VM} \cdot \hat{n})^2$$

$$|t|_{\mathrm{proj}} = (|t|_x, |t|_{\hat{n}}, |t|_z, |t|_E)$$

Wedge Cut

Want phase space where $|t|_{\hat{n}}$ dominates

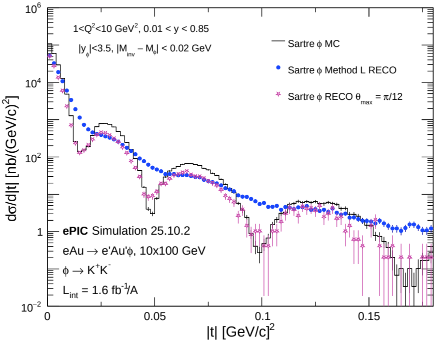


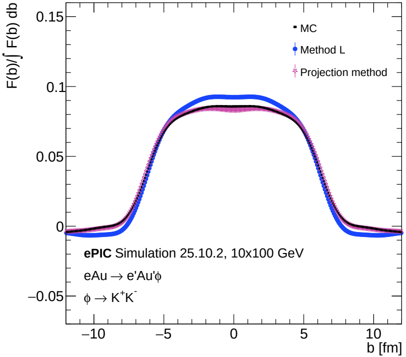


Get angle btw $|t|_{\hat{n}}$ and $|t|_{e'}$ direction:

$$
\begin{aligned}
|t| &= \Delta^2 \\
\Delta_x &= \Delta_\perp \sin(\omega) \\
\Delta_y &= \Delta_\perp \cos(\omega) \\
\omega_{\max} &= \tan^{-1}\left(\frac{\Delta_x}{\Delta_y}\right)
\end{aligned}
$$

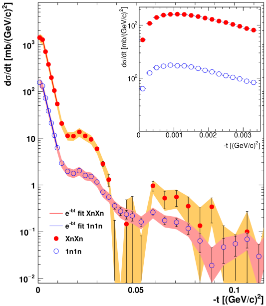
- Define $\Delta_x = \sqrt{|t_x|}$ to be in $\hat{x} = \hat{n} \times \hat{p}_e$ direction (e' direction)
- Cut wedge of angle $\omega_{\max}$ from $\hat{n}$-direction ($\Delta_y = \sqrt{|t|_{\hat{n}}}$)

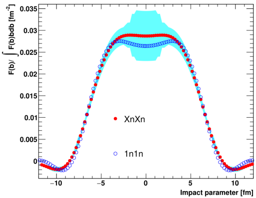




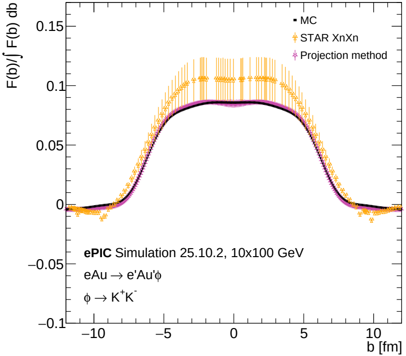
Significant improvement in both distributions

Small errors in minima = large errors in density





STAR arxiv: 1702.07705



- Need precise location of minima
- Smaller $|b|$ determined by larger $|t|$

What are we doing with this?

Gluon Saturation in Early Running of ePIC/EIC

- Establishing the non-linear QCD regime is identified as one of most critical EIC goals
- Diffractive cross-sections very sensitive to onset of non-linear dynamics in QCD $\sigma \propto g(x, Q^2)^2$

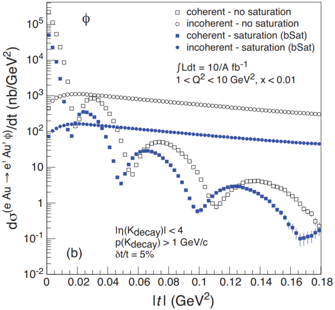
"An early measurement of coherent diffraction in e+A collisions at the EIC would provide the first unambiguous evidence for gluon saturation" - YR

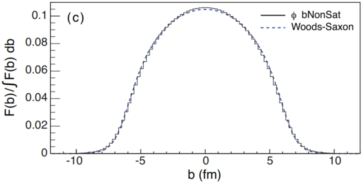
	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

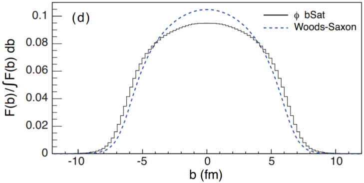
- At HERA: diffractive events made up $\approx$ 10–15% of the total $e + p$ cross-section
- Saturation models predict at EIC: more than 20% of the cross-section will be diffractive

Roadmap to Physics Impact Study

1. Generate Sartre non-saturated files
    - Currently I've been working with saturated simulations
2. Compare the $|t|$ distributions
3. **Transform and compare spatial distributions**







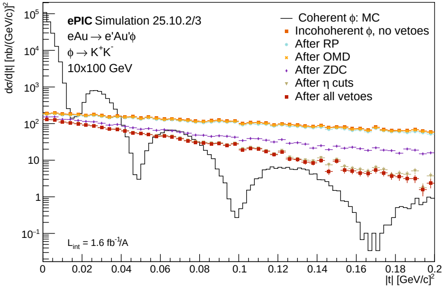
Toll and Ullrich arXiv:1211.3048

Need to get rid of incoherent background

Incoherent Issues Solved

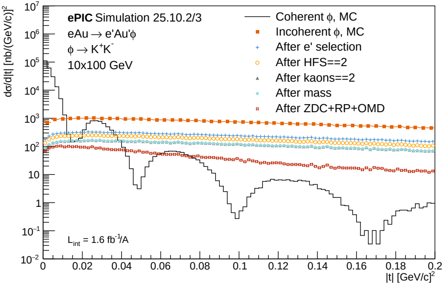
At collab meeting in Jan:

- Expected more suppression at low $|t|$



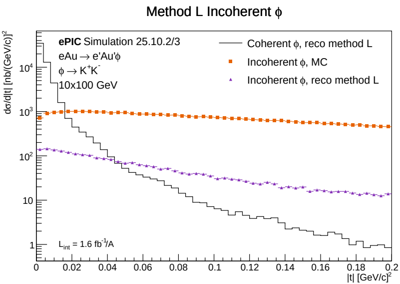
Now:

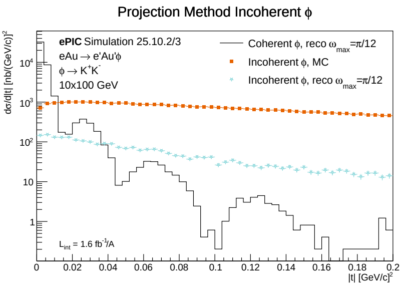
- Incoherent distribution as expected



- Compare final $|t|$ distributions where **coherent reco is same as incoherent**

Incoherent $|t|$ Distributions



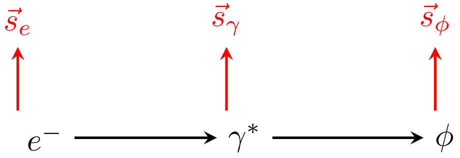


Still only able to resolve first dip

Removing the Incoherent Background

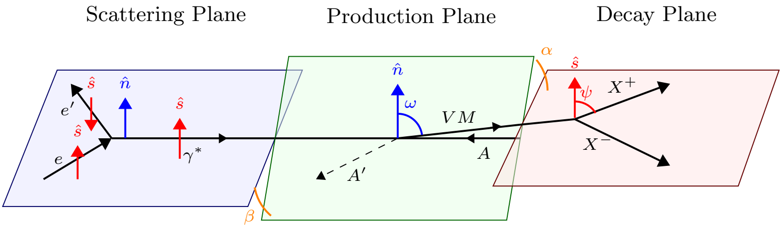
Statistically separate coherent from incoherent events

- Exploit decay pattern $\rightarrow$ determine fraction of coherently produced VMs
- Utilize polarized *e* beams
  - Polarized *e* can undergo a **spin flip**
  - Tansfers polarization to γ^*
  - VM inherits polarization



Spin transfer through spin-0 Pomeron

Spin-based Separation



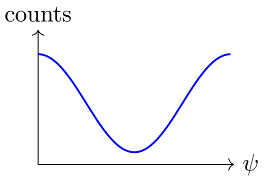
- **Coherent events:**
  - *e* spin flips: clean spin transfer $e \to \gamma^* \to$ VM
    - Observed at HERA arXiv:0910.5831
  - VM's spin direction is fixed
  - Project momentum of VM decay daughter onto VM spin direction $\to$ decay shows a $\cos(2\psi)$ modulation
    - Experimentally observed at STAR arxiv:2204.01625
- **Incoherent events:**
  - *e* spin does not flip $\to$ spin transfer is lost
  - VM spin direction random
  - Flat ψ distribution

Why the Spin-Based Projection Method Works

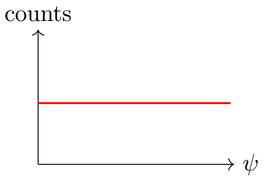
- Coherent events preserve the spin correlation
- Incoherent events typically do not
- Momentum-space separation fails at large $|t|$
  - Spin alignment survives

Pomeron spin-0: ensures e polarization transferred to VM

  - Decay pattern a direct tag of coherence

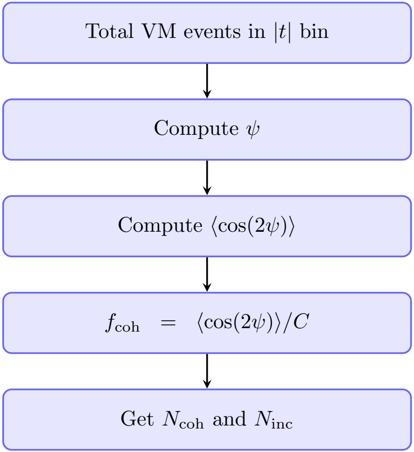


Coherent: $\cos(2\psi)$ modulation



Incoherent: flat distribution

Extracting the Coherent $|t|$ Distribution



For each $|t|$ bin:

1. Reconstruct VM
2. Compute ψ for each event. C = electron spin-flip probability:

$$\boxed{f_{coh}(|t|) = \frac{\langle\cos(2\psi)\rangle}{C}}$$

3. **Separate coherent and incoherent events**

$$N_{coh}(|t|) = f_{coh}(|t|)\, N_{tot}(|t|)$$
$$N_{inc}(|t|) = N_{tot} - N_{coh}$$

Summary

Solved outstanding incoherent issues

- Clear plan for phase II

Objectives:

- Finish updating everything:
  - AN note, Github $\rightarrow$ Zenedo
- Statistically separate incoherent and coherent events
- Analyze saturation effects
- ML for deconvolution